Executive Summary

The *Printed Wiring Board Surface Finishes Cleaner Technologies Substitutes Assessment: Volume 1* is a technical document that presents comparative risk, competitiveness, and resource requirements information on six technologies for performing the surface finishing function during printed wiring board (PWB) manufacturing. Surface finishing technologies are used by PWB manufacturers to deposit a coating on the outside surfaces of the PWB that provides a solderable surface for future assembly, while also protecting the surface from contamination. The technologies evaluated include hot air solder leveling (HASL), electroless nickel/immersion gold (nickel/gold), electroless nickel/immersion palladium/immersion gold (nickel/palladium/gold), organic solderability preservative (OSP), immersion silver, and immersion tin. Volume I describes the surface finishing technologies, methods used to assess the technologies, and Cleaner Technologies Substitutes Assessment (CTSA) results. Volume II contains appendices, including detailed chemical properties and methodology information.

Information presented in the CTSA was developed by the U.S. Environmental Protection Agency (EPA) Design for the Environment (DfE) Printed Wiring Board (PWB) Project and the University of Tennessee (UT) Center for Clean Products and Clean Technologies. The DfE PWB Project is a voluntary, cooperative partnership among EPA, industry, public-interest groups, and other stakeholders to promote implementation of environmentally beneficial and economically feasible manufacturing technologies by PWB manufacturers. Project partners participated in the planning and execution of this CTSA by helping define the scope and direction of the CTSA, developing project workplans, reviewing technical information contained in this CTSA and donating time, materials, and their manufacturing facilities for project research. Much of the process-specific information presented here was provided by chemical suppliers for the PWB industry, PWB manufacturers who completed project information requests, and PWB manufacturers who volunteered their facilities for a performance demonstration of the baseline and alternative technologies.

The CTSA is intended to provide PWB manufacturers with information that can assist them in making decisions that incorporate environmental concerns, along with performance and cost information, when choosing a surface finishing technology. The DfE PWB Project is especially designed to assist PWB manufacturers who may not have the resources or expertise to compare surface finishing technologies. The primary audience for the CTSA is environmental health and safety personnel, chemical and equipment manufacturers and suppliers in the PWB manufacturing industry, PWB assembly shops, community groups concerned about community health risks, and other technically informed decision-makers.

I. DESIGN FOR THE ENVIRONMENT PRINTED WIRING BOARD PROJECT

The DfE PWB Project is a joint effort of the EPA DfE Program and the UT Center for Clean Products and Clean Technologies in voluntary and cooperative partnerships with the PWB industry national trade association, the IPC-Association Connecting Electronics Industries (IPC); individual PWB manufacturers and suppliers; and public-interest organizations, including the Silicon Valley Toxics Coalition.

EPA's Design for the Environment Program

The EPA DfE Program was established by the Office of Pollution Prevention and Toxics to use EPA's expertise and leadership to facilitate information exchange and research on risk reduction and pollution prevention opportunities. DfE works on a voluntary basis with industry sectors to evaluate the risks, performance, costs, and resource requirements of alternative chemicals, processes, and technologies.

Additional goals of the program include:

- Changing general business practices to incorporate environmental concerns.
- Helping individual businesses undertake environmental design efforts through the application of specific tools and methods.

DfE Partners include:

- industry;
- professional institutions;
- academia;
- public-interest groups; and
- other government agencies.

In part, the project is an outgrowth of industry studies to identify key cleaner technology needs in electronic systems manufacturing. These studies include *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics Industry* (MCC, 1993), the *Electronics Industry Environmental Roadmap* (MCC, 1994), and the *National Technology Roadmap for Electronic Interconnections* (IPC, 1996). The first two studies identified environmental issues as priority targets for improvement by industry, while concluding that improvement would be accomplished most effectively through collaboration with government, academia, and the public. The final study cited the development of non-tin/lead metallic or organic coatings to retain solderability characteristics as an industry need over the near term. The potential for improvement in these areas led EPA's DfE Program to forge the working partnerships that resulted in the DfE PWB Project.

Since its inception in 1994, the PWB Project has fostered open and active participation in addressing environmental challenges faced by the PWB industry. The Project also has identified, evaluated, and disseminated information on viable pollution prevention opportunities in the industry; conducted a study of industry pollution prevention and control practices; and completed a study of making holes conductive alternatives, among other project efforts. Over the long-term, the Project seeks to encourage companies to consider implementing cleaner technologies that will improve the environmental performance and competitiveness of the PWB industry. Toward this goal, the CTSA presents the complete set of information developed by the Project on the risk, competitiveness (e.g., cost and performance), and resource requirements of cleaner technologies for applying a surface finish to a PWB.

II. OVERVIEW OF SURFACE FINISHING TECHNOLOGIES

Until the late 1980s, virtually all PWB manufacturers employed a HASL process to apply the final surface finish to PWBs. The HASL process applies a thin layer of solder to the panel surface by submerging the panel in molten solder, then removing the excess solder with an air knife as the panel is removed. Although the traditional HASL process is a mature technology that produces reliable surface connections, the finish has become limiting with respect to state-of-the-art component technology that requires special assembly. It is also a significant source of lead consumption in the PWB manufacturing process. In recent years, the advancements in component technology, along with public and private concerns over the use of lead, have led the PWB industry to seek viable alternative surface finishes.

Process Description

Surface finishing processes typically consist of a series of sequential chemical processing stages separated by water rinse tanks. The process can either be operated in a vertical, non-conveyorized immersion-type mode, or in a horizontal, conveyorized mode. In either mode, selected baths may be operated at an elevated temperature to facilitate required chemical reactions, or agitated to improve contact between the panels and the bath chemistry. Agitation methods employed by PWB manufacturers include panel agitation, air sparging, and fluid circulation pumps.

Most process baths are followed by a water rinse tank to remove drag-out (i.e., the clinging film of process solution covering the rack and boards when they are removed from a tank). Rinsing is necessary to clean the surface of the rack and boards to avoid contaminating subsequent process baths. Many PWB manufacturers employ a variety of rinse water reduction methods to reduce rinse water usage and consequent wastewater generation rates. The nature and quantity of wastewater generated from surface finishing process lines are discussed in Section 3.1, Source Release Assessment, while rinse water reduction techniques are discussed in Section 6.1, Pollution Prevention.

In the non-conveyorized mode, etched panels, covered with solder mask, are loaded onto a rack and processed through the surface finishing process line. Racks may be manually moved from tank to tank, or moved by a manually-controlled hoist or other means. Process tanks usually are open to the atmosphere. To reduce volatilization of chemicals from the bath or worker exposure to volatilized chemicals, process baths may be equipped with a local ventilation system, such as a push-pull system, bath covers for periods of inactivity, or floating plastic balls. Conveyorized systems typically are fully enclosed, with air emissions vented to a control technology or to the air outside the plant.

The HASL process combines wet chemistry steps, similar to those described above, with mechanical HASL equipment. First, panels are passed through a series of wet chemistry cleaning and etching steps to prepare the surface of the panel for the solder. Then, the solder is applied to the panel by dipping it into molten solder and removing the excess with high pressure air. After leaving the HASL machine, panels are cleaned by a water-based, high pressure rinse system.

Generic Process Steps and Bath Sequences of Surface Finishing Technologies

Figure ES-1 presents the generic process steps and typical bath sequences evaluated in the CTSA. The process baths depicted in the figure are an integration of the various products submitted for evaluation by chemical suppliers within a technology category. For example, two different OSP processes were submitted by chemical suppliers for evaluation in the CTSA, and these and other suppliers offer additional OSP processes that may have slightly different bath chemistries or bath sequences. In addition, the bath sequences (bath order and rinse tank configuration) were aggregated from data collected from various PWB facilities using the different surface finishing technologies. Thus, Figure ES-1 lists the types and sequences of baths in generic process lines; however, the types and sequences of baths in actual lines may vary.

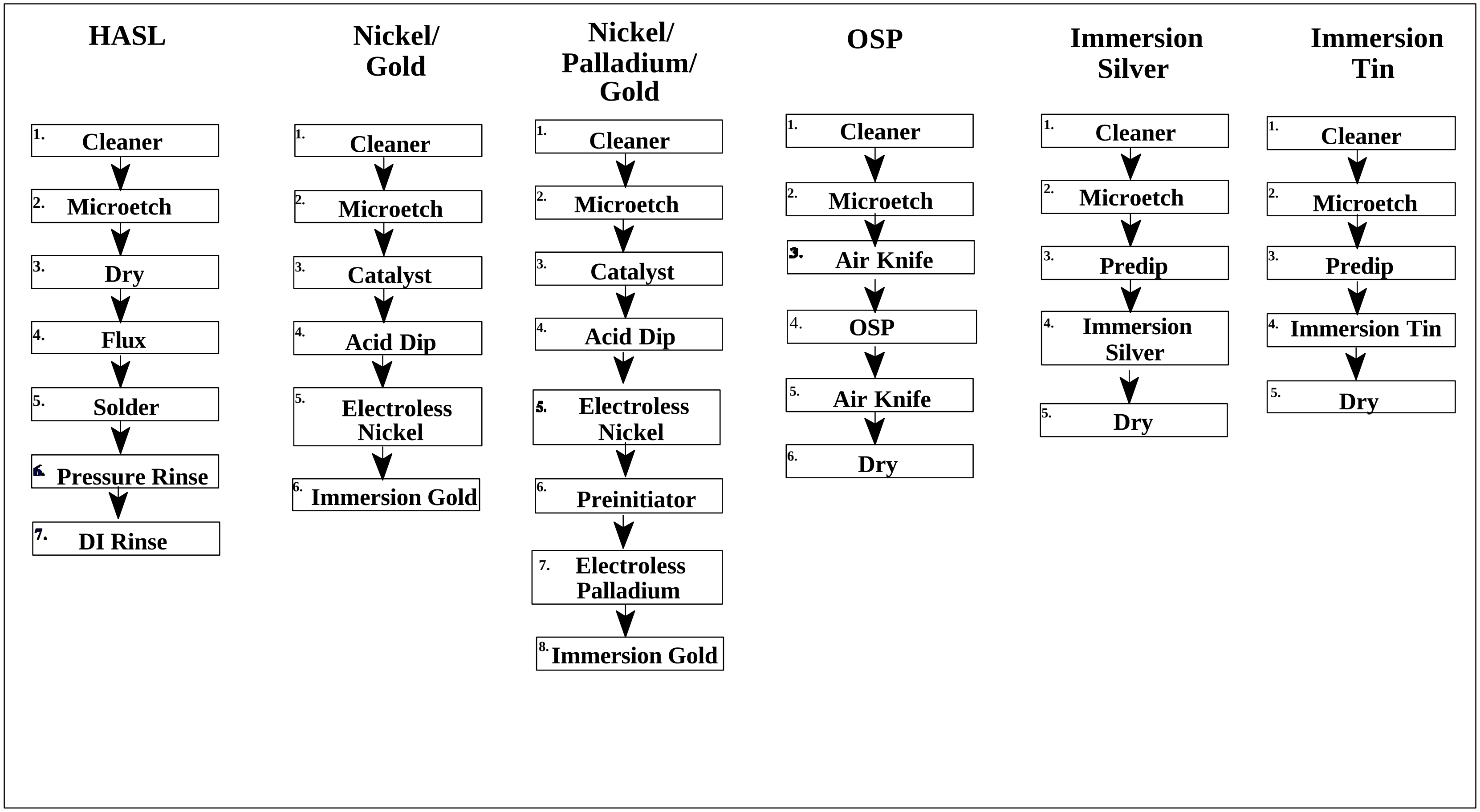
Table ES-1 presents the processes evaluated in the CTSA. These are distinguished both by process technology and equipment configuration (non-conveyorized or conveyorized). The non-conveyorized HASL process is the industry standard for performing the surface finishing function and is the baseline process against which alternative technologies and equipment configurations are compared.

Table ES-1. Surface Finishes Evaluated in the CTSA

Surface Finishing Technology	Equipment Configuration	
	Non-Conveyorized	Conveyorized
HASL (Baseline)	X	X
Nickel/Gold	X	
Nickel/Palladium/Gold	X	
OSP	X	X
Immersion Silver		X
Immersion Tin	X	X

III. CLEANER TECHNOLOGIES SUBSTITUTES ASSESSMENT METHODOLOGY

The CTSA methodology is a means of systematically evaluating and comparing human health and environmental risk, competitiveness (e.g., performance and cost), and resource requirements of traditional and alternative chemicals, manufacturing methods, and technologies that can be used to perform the same function. The publication, *Cleaner Technologies Substitutes Assessment: A Methodology & Resource Guide* (Kincaid et al., 1996), presents the basic CTSA methodology in detail. Particular methods used in this assessment are described in chapters 2 through 6 of this document, and in the appendices (*Printed Wiring Board Surface Finishes Cleaner Technologies Substitutes Assessment: Volume 2).*



Note: One or more intermediate rinse steps typically separate the process steps listed above. For simplicity, these intermediate rinse steps have not been included in the diagram.

Figure ES-1. Typical Process Steps for Surface Finishing Technologies

Key to the successful completion of any CTSA is the active participation of manufacturers and their suppliers. This assessment was open to any surface finishing chemical supplier who wanted to submit a technology, provided the technology met the following criteria:

- it is an existing or emerging technology; and
- the equipment and facilities are available to demonstrate its performance.

In addition, suppliers were required to provide information about their technologies, including complete chemical product formulation data, process schematics, process characteristics and constraints (e.g., cycle time, bath immersion time, thickness of deposit), bath replacement criteria, and cost information.

Issues Evaluated

The CTSA evaluated a number of issues related to the risk, competitiveness, and resource requirements (conservation) of surface finishing technologies. These include the following:

- Risk: occupational health risks, public health risks, ecological hazards, and process safety concerns.
- Competitiveness: technology performance, cost, and regulatory status.
- Conservation: energy and natural resource use.

Occupational and public health risk information is for chronic exposure to long-term, day-to-day releases from a PWB facility, rather than short-term, acute exposures to high levels of hazardous chemicals as could occur with a fire, spill, or periodic release. Risk information is based on exposures estimated for a typical, model facility, rather than exposures estimated for a specific facility. Ecological risks are evaluated for aquatic organisms that could be exposed to surface finishing chemicals in wastewater discharges. Process safety concerns are summarized from material safety data sheets (MSDSs) for the technologies and process operating conditions.

Technology performance is based on a snapshot of the performance of the surface finishing technologies at volunteer test sites in the United States and abroad. Panels were tested under accelerated aging conditions (three weeks of 85 ^{o}C/85 percent humidity), followed by thermal shock testing, and mechanical shock testing to distinguish variability in the performance of the surface finish. Comparative costs of the surface finishing technologies were estimated with a hybrid cost model that combines traditional costs with simulation modeling and activity-based costs. Costs are presented in terms of dollars per surface square feet (ssf) of PWB produced.

Federal environmental regulatory information is presented for the chemicals in the surface finishing technologies. This information is intended to provide an indication of the regulatory requirements potentially associated with a technology, but not to serve as regulatory guidance.

Quantitative resource consumption data are presented for the comparative rates of energy and water use of the surface finishing technologies. The consumption of other non-renewable resources such as process chemicals and metals also are analyzed.

Finally, a socio-economic costs and benefits analysis of the operation of the surface finishing process line is presented for each of the process alternatives. The private costs and benefits to the manufacturer resulting from the use of a technology, as well as the external costs and benefits to workers and the community are evaluated quantitatively or qualitatively.

Data Collection

Determining the risks of the baseline and alternative surface finishing technologies required information on the chemical products for each process. Chemical information provided by chemical suppliers included the following publicly-available sources of information: MSDSs for the chemical products in their surface finishing technology lines and Product Data Sheets, which are technical specifications prepared by suppliers for PWB manufacturers that describe how to mix and maintain the chemical baths. Suppliers also were asked to provide the identities and concentrations of proprietary chemical ingredients to the project.

Data Collection Forms

Appendix A in Volume II of the CTSA presents data collection forms used by the project, including the following:

- The PWB Workplace Practices Questionnaire, which requested detailed information on facility size, process characteristics, chemical consumption, and worker activities related to chemical exposure, water consumption, and wastewater discharges.
- The Facility Background Information Sheet (developed from the PWB Workplace Practices Questionnaire) which was sent to PWB facilities participating in the Performance Demonstration prior to their surface technology test date. This sheet requested detailed information on facility and process characteristics, chemical consumption, and worker activities related to chemical exposure, water consumption, and wastewater discharges.
- The Observer Data Sheet, which was used by an on-site observer to collect data during the Performance Demonstration. In addition to ensuring that the performance test was performed according to the agreed-upon test protocol, the on-site observer collected measured data, such as bath temperature and process line dimensions, and checked survey data for accuracy.
- The Supplier Data Sheet, which included information on chemical cost, equipment cost, water consumption rates, product constraints, and the locations of test sites for the Performance Demonstration.

Chemical Information

Appendix B presents chemical properties and selected environmental fate properties for the non-proprietary chemicals in surface finishing chemical products. Proprietary chemical ingredients are not included to protect proprietary chemical identities. Properties that were measured or estimated (using a variety of standard EPA methods) included melting point, solubility, vapor pressure, octanol-water partition coefficient, boiling point, and flash point.

These properties can be used to determine the environmental fate of the surface finishing chemicals when they are released to the environment.

Health Hazard Assessments

Inherent in determining the risk associated with the surface finishing chemicals is a determination of the hazard or toxicity of the chemicals. Human health hazard information for non-proprietary chemicals is presented in Section 3.3. Detailed toxicity data for proprietary chemicals are not included to maintain the secrecy of the proprietary chemical formulations. Many of the chemicals in the surface finishing chemical products have been studied to determine their health effects, and data from those studies are available in published scientific literature. In order to collect available testing data for the surface finishing chemicals, literature searches were conducted using standard chemical references and online databases, including EPA's Integrated Risk Information System (IRIS) and the National Library of Medicine's Hazardous Substances Data Bank (HSDB).

For many of the chemicals, EPA has identified chemical exposure levels that are known to be hazardous if exceeded or met (e.g., no- or lowest-observed-adverse-effect level [NOAEL or LOAEL]), or levels that are protective of human health (reference concentration [RfC] or reference dose [RfD]). These values were taken from online databases and published literature. For many of the chemicals lacking toxicity data, EPA's Structure-Activity Team (SAT) estimated human health concerns based on analogous chemicals. Hazard information is combined with estimated exposure levels to develop an estimate of the risk associated with each chemical.

Ecological Hazard Assessments

Similar information was gathered on the ecological effects that may be expected if surface finishing chemicals are released to water. Acute and chronic toxicity values were taken from online database searches (TOXNET and ACQUIRE), published literature, or were estimated using structure-activity relationships if measured data were not available. Based on the toxicity values, surface finishing chemicals were assigned concern concentrations (CCs). A CC is the concentration of a chemical in the aquatic environment which, if exceeded, may result in significant risk to aquatic organisms. CCs were determined by dividing acute or chronic toxicity values by an assessment factor (ranging from one to 1,000) that incorporates the uncertainty associated with toxicity data.

Limitations

There are a number of limitations to the project, both because of the limit of the project's resources, the predefined scope of the project, and uncertainties inherent to risk characterization techniques. Some of the limitations related to the risk, competitiveness, and conservation components of the CTSA are summarized below. More detailed information on limitations and uncertainties for a particular portion of the assessment is given in the applicable sections of this document. A limitation common to all components of the assessment is that the surface finishing chemical products assessed in this report were voluntarily submitted by participating suppliers and may not represent the entire surface finishing technology market.

Risk Screening and Comparison

The risk screening and comparison is a screening level assessment of multiple chemicals used in surface finishing technologies. The focus of the risk characterization is chronic (long-term) exposure to chemicals that may cause cancer or other toxic effects rather than acute toxicity from brief exposures to chemicals. The exposure assessment and risk characterization use a "model facility" approach, with the goal of comparing the exposures and health risks of the surface finishing process alternatives to the baseline non-conveyorized HASL technology. Characteristics of the model facility were aggregated from questionnaire data, site visits, and other sources. This approach does not result in an absolute estimate or measurement of risk.

The estimates of exposure and risk reflect only a portion of the potential exposures within a PWB manufacturing facility. Many of the chemicals found in surface finishing technologies also may be present in other process steps of PWB manufacturing, and other risk concerns for human health and the environment may occur from these other process steps. Incremental reduction of exposures to chemicals of concern from a surface finishing process, however, will reduce cumulative exposures from all sources in a PWB facility. Uncertainties and key assumptions are described further in Chapter 3, Risk Screening and Comparison.

Competitiveness

The Performance Demonstration was designed to provide a snapshot of the performance of different surface finishing technologies. The test methods used to evaluate performance were intended to indicate characteristics of a technology's performance, not to define parameters of performance or to substitute for thorough on-site testing. Because the test sites were not chosen randomly, the sample may not be representative of all PWB manufacturing facilities in the United States (although there is no specific reason to believe they are not representative).

The cost analysis presents comparative costs of using a surface finishing technology in a model facility to produce 260,000 ssf of PWB. As with the risk characterization, this approach results in a comparative evaluation of cost, not an absolute evaluation or determination. The cost analysis focuses on the private costs that would be incurred by facilities implementing a technology. However, the analysis is limited to costs that are solely attributable to the surface finishing process and does not evaluate costs associated with product quality or wastewater treatment. Community benefits or costs, such as reduced health effects to workers or the effects on jobs from implementing a more efficient surface finishing technology, also are not quantified. The Social Benefits/Costs Assessment (see Section 7.2), however, qualitatively evaluates some of these external benefits and costs.

The regulatory information contained in the CTSA may be useful in evaluating the benefits of implementing processes which no longer contain chemicals that trigger compliance issues; however, this document is not intended to provide compliance assistance. If the reader has questions regarding compliance concerns, they should contact their federal, state, or local authorities.

Conservation

The analysis of energy and water consumption is also a comparative analysis, rather than an absolute evaluation or measurement. Similar to the cost analysis, consumption rates were estimated based on using a surface finishing technology in a model facility to produce 260,000 ssf of PWB.

IV. CLEANER TECHNOLOGIES SUBSTITUTES ASSESSMENT RESULTS

Occupational Exposures and Health Risks

Health risks to workers are estimated for inhalation exposure to vapors and aerosols from surface finishing baths and for dermal exposure to surface finishing bath chemicals. Inhalation exposure estimates are based on the assumptions that emissions to indoor air from conveyorized lines are negligible, that the air in the process room is completely mixed and chemical concentrations are constant over time, and that no vapor control devices (e.g., bath covers) are used in non-conveyorized lines. Dermal exposure estimates are based on the conservative assumptions that workers do not wear gloves and that all non-conveyorized lines are operated by manual hoist. Dermal exposure to line operators on non-conveyorized lines is estimated for routine line operation and maintenance (e.g., bath replacement, filter replacement), and on conveyorized lines for bath maintenance activities alone.

Based on the number of chemicals with risk results above concern levels, some alternatives to the non-conveyorized HASL process appear to pose lower occupational risks (immersion silver, conveyorized and non-conveyorized immersion tin, and conveyorized HASL), some may pose similar levels of risk (conveyorized and non-conveyorized OSP), and some may pose higher risk (nickel/gold and nickel/palladium/gold). Surface finishing chemicals of concern for potential occupational risk from inhalation are shown in Table ES-2.

There also are occupational risk concerns for dermal contact with chemicals in the non-conveyorized HASL, nickel/gold, nickel/palladium/gold, OSP, and immersion tin processes, and the conveyorized HASL and OSP processes. Table ES-3 presents chemicals of concern for potential occupational risk from dermal contact.

Table ES-2. Surface Finishing Chemicals of Concern for Potential Occupational Inhalation Risk

Chemical	Process (Non-Conveyorized, 260,000 ssf) [a]			
	HASL	Nickel/Gold	Nickel/Palladium/Gold	OSP
Alkyldiol		X	X	
Ethylene glycol	X			X
Hydrochloric acid		X	X	
Hydrogen peroxide		X	X	
Nickel sulfate		X	X	
Phosphoric acid		X	X	
Propionic acid			X	

[a] Non-conveyorized immersion silver process not evaluated. Occupational exposure and risk from all conveyorized process configurations are below concern levels.
X Line operator risk results above concern levels (non-cancer health effects).

Table ES-3. Chemicals of Concern for Potential Dermal Risks

Chemical	HASL (NC)	HASL (C)	Nickel/Gold (NC)	Nickel/ Palladium/Gold (NC)	OSP (NC)	OSP (C)	Immersion Tin (NC)
Ammonia compound A				X			
Ammonium chloride			X				
Ammonium hydroxide			X	X			
Copper ion					XX	XX	
Copper salt C					XX	X	
Copper sulfate pentahydrate	XX	XX	XX	XX	XX	XX	
Ethylene glycol monobutyl ether							X
Hydrogen peroxide			X	X			
Inorganic metallic salt B			XX	XX			
Lead	†	†					
Nickel sulfate			XX	XX			
Urea compound C							X

Note: No risk results were above concern levels for the conveyorized immersion silver or conveyorized immersion tin processes.
X Line operator risk results above concern levels (non-cancer health effects).
XX Line operator and laboratory technician risk results above concern levels (non-cancer health effects).
†: Risk indicators were not calculated for lead as with the other chemicals (see Section 3.4.6). Other information, however, indicates that incidental ingestion of lead from contact with hands could result in lead exposure at levels of concern.
C: Conveyorized (horizontal) process configuration.
NC: Non-conveyorized (vertical) process configuration.

The non-conveyorized nickel/gold process contains the only chemical for which an occupational cancer risk has been estimated (inorganic metallic salt A). The line operator inhalation exposure estimate for inorganic metallic salt A results in an estimated upper bound excess individual life time cancer risk of 2×10^{-7} (one in five million) based on high end exposure. Cancer risks less than 1×10^{-6} (one in one million) are generally considered to be of low concern. Risks to other types of workers[1] were assumed to be proportional to the average amount of time spent in the process area, which ranged from 12 to 69 percent of the risk for a line operator.

Other identified chemicals in the surface finishing processes are suspected or known carcinogens. Lead and thiourea have been determined by the International Agency for Research on Cancer (IARC) to be possible human carcinogens (IARC Group 2B); lead has also been classified by EPA as a probable human carcinogen (EPA Class B2). Lead is used in tin-lead solder in the HASL process. Thiourea is used in the immersion tin process. Urea compound B, a confidential ingredient in the nickel/gold and nickel/palladium/gold processes, is possibly carcinogenic to humans. Exposure for workers from these chemicals has been estimated, but cancer potency and cancer risks are unknown. Additionally, strong inorganic and acid mists of sulfuric acid have been determined by IARC to be a human carcinogen (IARC Group 1). Sulfuric acid is used in diluted form in every surface finishing process in this evaluation. It is not expected, however, to be released to the air as a strong acid mist. There are potential cancer risks to workers from these chemicals, but because there are no slope factors, the risks cannot be quantified.

For non-cancer risk, risk indicators exceeding concern levels – a hazard quotient (HQ) greater than one, a margin of exposure (MOE) based on NOAEL lower than 100, or MOE based on a LOAEL lower than 1,000 – were estimated for occupational exposures to chemicals in the non-conveyorized and conveyorized HASL processes, non-conveyorized nickel/gold process, non-conveyorized nickel/palladium/gold process, non-conveyorized and conveyorized OSP processes, and the non-conveyorized immersion tin process.

Based on calculated occupational exposure levels, there may be adverse health effects to workers exposed to chemicals with a HQ exceeding 1.0 or an MOE less than 100 or 1,000. It should be emphasized, however, that these conclusions are based on screening level estimates. These numbers are used here for relative risk comparisons between processes and should not be used as absolute indicators for actual health risks to surface finishing line workers.

Worker blood-lead levels measured at one PWB manufacturing facility were below any federal regulation or guideline for workplace exposure. Modeling data, however, indicate that blood-lead levels could exceed recommended levels for an adult and fetus, given high incidental ingestion rates of lead from handling solder. Although these results are highly uncertain, this indicates the need for good personal hygiene for HASL line operators, especially wearing gloves and hand washing to prevent accidental hand-to-mouth ingestion of lead.

[1] These include laboratory technicians, maintenance workers, and wastewater treatment operators. Other types of workers may be present for shorter or longer times.

Public Exposures and Health Risks

Potential public health risks was estimated for inhalation exposure for the general public living near a PWB facility. Public exposure estimates are based on the assumption that emissions from both conveyorized and non-conveyorized process configurations are vented to the outside. The risk indicators for ambient exposures to humans, although limited to airborne releases, indicate low concern for nearby residents. The upper bound excess individual cancer risk for nearby residents from inorganic metallic salt A in the non-conveyorized nickel/gold process was estimated to be from approaching zero to 2×10^{-11} (one in 50 billion). This chemical has been classified as a human carcinogen.[2] All hazard quotients are less than one for ambient exposure to the general population, and all MOEs for ambient exposure are greater than 1,000 for all processes, indicating low concern from the estimated air concentrations for chronic non-cancer effects.

Estimated ambient air concentrations of lead from a HASL process are well below EPA air regulatory limits for lead, and risks to the nearby population from airborne lead are expected to be below concern levels.

Ecological Hazards

Ecological risk indicators (RI_{ECO}) were calculated for non-metal surface finishing chemicals that may be released to surface water. Risk indicators for metals are not used for comparing alternatives because it is assumed that on-site treatment is targeted to remove metal so that permitted concentrations are not exceeded. Estimated surface water concentrations for non-metals exceeded the CC for the processes as shown in Table ES-4. CCs are discussed in more detail in Section 3.3.3.

Table ES-4. Aquatic Risk of Non-Metal Chemicals of Concern

Chemical	HASL (NC)	HASL (C)	OSP (NC)	OSP (C)	Immersion Silver (C)	Immersion Tin (NC)
1,4-Butenediol	X					
Alkylaryl imidazole			X	X		
Alkylaryl sulfonate	X	X				
Hydrogen peroxide	X	X			X	
Potassium peroxymonosulfate	X	X				X

Estimated surface water concentration > CC after publicly owned treatment works (POTW) treatment.

[2] A cancer classification of known human carcinogen has been assigned by either the EPA, IARC, and/or NTP. Further details about the carcinogen classification are not provided in order to protect the confidential chemical identity.

Process Safety

In order to evaluate the chemical safety hazards of the various surface finishing technologies, MSDSs for chemical products used with each surface finish were reviewed. Table ES-5 summarizes the hazardous properties listed on MSDSs for surface finishing chemical products. Other potential chemical hazards posed by surface finishing chemicals include either the hazardous decomposition of chemical products, or chemical product incompatibilities with other chemicals or materials.

Table ES-5. Hazardous Properties of Surface Finishing Chemical Products

Process	No. of MSDS [a]	Hazardous Property							
		F	C	E	FH	CO	O	SRP	U
HASL [b]	33	1		1	3	4	1	1	1
Nickel/Gold	19					8	1	1	
Nickel/Palladium/Gold	18					12	1	1	
OSP	9	1			2	4	1	1	
Immersion Silver	4			1	1	2	1		1
Immersion Tin	14			1		7			

[a] For alternative processes with more than one product line, the hazard data reported represent the most hazardous bath of each type for the two product lines (e.g., of the microetch baths from the two product lines, the one with the most hazardous chemicals is reported).
[b] Formulations for HASL process baths were unavailable because cleaner and microetch bath chemistries are not made specifically for the HASL process. Hazards reported for HASL bath types were reported as the worst case of the results of similar baths from other processes.
F = Flammable; C = Combustible; E = Explosive; FH = Fire Hazard; CO = Corrosive; O = Oxidizer; SRP = Sudden Release of Pressure; U = Unstable.

Several unique process safety concerns arise from the operation of the HASL process. Solder eruptions during start-up can lead to solder splattering onto workers causing serious burns. The HASL process also poses a fire hazard due to the build-up of residual carbon from the use of oil-based flux or other flammable materials. Other safety concerns include worker exposure to acids in the flux, accidental contact with the molten solder, or exposure to the other chemical hazards on the process line.

Work-related injuries from equipment, improper use of equipment, bypassing equipment safety features, failure to use personal protective equipment, and physical stresses that may appear gradually as a result of repetitive motion are all potential process safety hazards to workers. Reducing the potential for work-related injuries is critical in an effective and ongoing safety training program. Appropriate training can help reduce the number of work-related accidents and injuries regardless of the technology used.

Performance

The performance of the surface finishing technologies was tested using production run tests following a strict testing protocol. Functional test boards were fabricated using a complex test board design (a modified version of the IPC-B-24 board) developed by the Circuit Card Assembly and Materials Task Force (CCAMTF). A surface finish was then applied to test boards at each of thirteen volunteer PWB manufacturing facilities. Test boards were then collected together and assembled at an assembly facility, using either a halide-free low-residue flux or a halide-containing water-soluble flux, before being tested under thermal and mechanical stress, and accelerated aging conditions. Additional residue testing was conducted to determine the mechanism of failure.

The test vehicle measured roughly 6" x 5.8" x 0.062" and was designed to contain at least 80 percent of the circuitry used in military and commercial electronics. The test vehicle also contained a variety of circuits, including high current low voltage (HCLV), high voltage low current (HVLC), high speed digital (HSD), high frequency (HF), stranded wire (SW), and other networks, which were used to measure current leakage. Overall, the vehicle provided 23 separate electrical responses for testing the performance of the surface finish. Types of electrical components in the HCLV, HVLC, HSD, and HF circuits included both plated through hole (PTH) and surface mounted components.

Test sites were submitted by suppliers of the technologies, and included production facilities and supplier testing facilities. Because the test sites were not chosen randomly, the sample may not be representative of all PWB manufacturing facilities (although there is no specific reason to believe that they are not representative). In addition, the number of test sites for each technology ranged from one to four. Due to the smaller number of test sites for some technologies, statistical relevance could not be determined.

The results of the performance testing showed that all of the surface finishes under study were very robust to the environmental exposures, with two exceptions. Failures during the mechanical shock testing, resulting in the separation of the surface mount components, were attributable to the severity of the testing, and were spread evenly across all finishing technologies, including the baseline HASL process. Failures in the high frequency, low pass filter circuits, resulting from open PTH, were found to be attributable to a combination of board fabrication materials and board design. From an overall contamination standpoint, the five non-HASL surface finishes performed as well, if not better than the HASL finish. The few solder joint cracking failures were greater with the HASL finish than with the alternative finishes.

Cost Analysis

Comparative costs were estimated using a hybrid cost model that combined traditional costs with simulation modeling and activity-based costs. The cost model was designed to determine the total cost of producing 260,000 ssf of PWB for each of the surface finishing technologies using a model facility concept. Total costs were normalized to a cost per ssf of PWB produced.

The cost components evaluated include capital costs (primary equipment, installation, and facility costs), materials costs (limited to chemical costs), utility costs (water, electricity, and natural gas costs), wastewater costs (limited to wastewater discharge cost), production costs (production labor and chemical transport costs), and maintenance costs (tank cleanup, bath setup, sampling and analysis, and filter replacement costs). Start-up costs for implementing a surface finishing technology, as well as the costs of other process changes that may be required to implement an alternative technology, were not considered in the cost evaluation. Other cost components that contribute to overall costs, but which also could not be quantified include quality costs, wastewater treatment cost, sludge recycling and disposal cost, and other solid waste disposal costs.

Cost analysis results are presented in Table ES-6. With the exception of the two technologies containing gold, an expensive precious metal, the results indicate that all of the other surface finishing alternatives were more economical than the baseline non-conveyorized HASL process. Three processes had a substantial cost savings of at least 50 percent of the cost per ssf over that of the baseline HASL process (conveyorized OSP at 72 percent, non-conveyorized OSP at 69 percent, and non-conveyorized immersion tin at 50 percent). Three other process alternatives realized a somewhat smaller cost savings over the baseline HASL process (conveyorized immersion tin at 31 percent, conveyorized immersion silver at 22 percent, and the conveyorized HASL process at 3 percent).

In general, conveyorized processes cost less than non-conveyorized processes. Chemical cost was the single largest component cost for all nine of the processes, with the cost of labor a distant second.

Regulatory Status

Discharges of surface finishing chemicals may be restricted by federal, state, or local air, water, or solid waste regulations, and releases may be reportable under the federal Toxic Release Inventory program. Federal environmental regulations were reviewed to determine the federal regulatory status of surface finishing chemicals.[3] Table ES-7 lists the number of chemicals used in each surface finishing technology that are subject to federal environmental regulations. Different chemical suppliers of a technology do not always use the same chemicals in their particular product lines. Thus, all of these chemicals may not be present in any one product line.

Resource Conservation

Energy and water consumption rates were evaluated for each of the surface finishing process alternatives. Other resource consumption by the surface finishing technologies was evaluated qualitatively due to the variability of factors that affect the consumption of these resources. Table ES-8 presents the energy and water consumption rates of the surface finishing technologies.

[3] In some cases, state or local requirements may be more restrictive than federal requirements. Due to resource limitations, however, only federal regulations were reviewed.

Table ES-6. Cost Analyses Results [a]

Surface Finishing Technology	Average Cost		Capital Cost		Chemical Cost		Water Cost		Electricity Cost	
	$/ssf	% change	$/ssf	% change	$/ssf`	% change	$/ssf	% change	$/ssf	% change
HASL, Non-conveyorized (BASELINE)	$ 0.36	--	$ 0.038	--	$ 0.288	-	$ 0.003	--	$ 0.003	--
HASL, Conveyorized	$ 0.35	-3%	$ 0.044	16%	$ 0.289	0%	$ 0.002	-20%	$ 0.002	-32%
Nickel/Gold, Non-conveyorized	$ 0.60	67%	$ 0.039	4%	$ 0.419	46%	$ 0.005	67%	$ 0.009	253%
Nickel/Palladium/Gold, Non-conveyorized	$ 1.54	328%	$ 0.083	119%	$ 1.235	329%	$ 0.008	191%	$ 0.016	507%
OSP, Non-conveyorized	$ 0.11	-69%	$ 0.008	-80%	$ 0.071	-75%	$ 0.002	-38%	$ 0.001	-53%
OSP, Conveyorized	$ 0.10	-72%	$ 0.012	-68%	$ 0.072	-75%	$ 0.001	-57%	$ 0.001	-69%
Immersion Silver, Conveyorized	$ 0.28	-22%	$ 0.044	17%	$ 0.203	-29%	$ 0.001	-57%	$ 0.003	11%
Immersion Tin, Non-conveyorized	$ 0.18	-50%	$ 0.015	-61%	$ 0.112	-61%	$ 0.004	46%	$ 0.002	-26%
Immersion Tin, Conveyorized	$ 0.25	-31%	$ 0.074	95%	$ 0.111	-61%	$ 0.003	-1%	$ 0.005	84%

Surface Finishing Technology	Natural Gas Cost		Wastewater Cost		Production Cost		Maintenance Cost	
	$/ssf	% change	$/ssf	% change	$/ssf	% change	$/ssf	% change
HASL, Non-conveyorized (BASELINE)	$ 0.000	---	$ 0.004	--	$ 0.016	---	$ 0.011	---
HASL, Conveyorized	$ 0.000	-50%	$ 0.003	-23%	$ 0.007	-53%	$ 0.007	-36%
Nickel/Gold, Non-conveyorized	$ 0.000	-100%	$ 0.008	86%	$ 0.076	381%	$ 0.042	275%
Nickel/Palladium/Gold, Non-conveyorized	$ 0.000	-100%	$ 0.014	222%	$ 0.101	539%	$ 0.080	610%
OSP, Non-conveyorized	$ 0.000	-24%	$ 0.003	-36%	$ 0.013	-19%	$ 0.013	13%
OSP, Conveyorized	$ 0.000	-65%	$ 0.002	-58%	$ 0.006	-65%	$ 0.008	-33%
Immersion Silver, Conveyorized	$ 0.001	59%	$ 0.002	-52%	$ 0.021	32%	$ 0.010	-15%
Immersion Tin, Non-conveyorized	$ 0.001	82%	$ 0.006	47%	$ 0.027	70%	$ 0.015	28%
Immersion Tin, Conveyorized	$ 0.001	171%	$ 0.005	10%	$ 0.034	118%	$ 0.017	46%

[a] Table lists costs and percent change in cost from the baseline.

Table ES-7. Regulatory Status of Surface Finishing Technologies

Process Chemical	Number of Chemicals Subject to Applicable Regulation														
	CWA				CAA			EPCRA			TSCA			RCRA Waste	
	304b	307a	311	Priority Pollutant	111	112b	112r	313	110	302a	8d HSDR	MTL	8a PAIR	P	U
HASL	1	1	4	1	3	3	1	6	1	3	3	4	3	-	-
Nickel/Gold	6	6	16	6	11	6	1	12	7	3	1	4	3	-	-
Nickel/Palladium/Gold	5	5	12	5	5	5	1	10	6	3	1	4	4	-	-
OSP	2	2	5	2	3	2	1	5	2	2	1	2	1	-	-
Immersion Silver	1	1	5	1	1	1	-	3	1	3	-	1	1	-	-
Immersion Tin	1	1	6	1	3	2	1	7	1	2	2	4	3	-	2

Abbreviations and definitions:

CAA **-** Clean Air Act
CAA 111 **-** Standards of Performance for New Stationary Sources of Air Pollutants -Equipment Leaks Chemical List
CAA 112b **-** Hazardous Air Pollutant
CAA 112r **-** Risk Management Program
CWA **-** Clean Water Act
CWA 304b **-** Effluent Limitations Guidelines
CWA 307a **-** Toxic Pollutants
CWA 311 **-** Hazardous Substances
CWA **-** Priority Pollutants
EPCRA **-** Emergency Planning and Community Right-to-Know Act
EPCRA 302a **-** Extremely Hazardous Substances
EPCRA 313 **-** Toxic Chemical Release Inventory
RCRA **-** Resource Conservation and Recovery Act
RCRA P Waste **-** Listed acutely hazardous waste
RCRA U Waste **-** Listed hazardous waste
SARA **-** Superfund Amendments and Reauthorization Act
SARA 110 **-** Superfund Site Priority Contaminant
SDWA **-** Safe Drinking Water Act
SDWA NPDWR **-** National Primary Drinking Water Rules
SDWA NSDWR **-** National Secondary Drinking Water Rules
TSCA **-** Toxic Substances Control Act
TSCA 8d HSDR **-** Health & Safety Data Reporting Rules
TSCA MTL **-** Master Testing List
TSCA 8a PAIR **-** Preliminary Assessment Information Rule

The rate of water consumption is directly related to the rate of wastewater generation. Several processes were found to consume less water than the HASL baseline, including conveyorized versions of the immersion silver and immersion tin technologies and both versions of the OSP process. Conveyorized processes were found to consume less water than non-conveyorized versions of the same process. Primary factors influencing the water consumption rate included the number of rinse tanks and the overall efficiency of the conveyorized processes.

Table ES-8. Energy and Water Consumption Rates of Surface Finishing Technologies

Process Type	Water Consumption (gal/ssf)	Energy Consumption (Btu/ssf)
HASL, Non-conveyorized (BASELINE)	1.24	218
HASL, Conveyorized	0.99	133
Nickel/Gold, Non-conveyorized	2.06	447
Nickel/Palladium/Gold, Non-conveyorized	3.61	768
OSP, Non-conveyorized	0.77	125
OSP, Conveyorized	0.53	73
Immersion Silver, Conveyorized	0.53	287
Immersion Tin, Non-conveyorized	1.81	289
Immersion Tin, Conveyorized	0.88	522

Energy consumption by the surface finishing technologies was driven primarily by the overall throughput efficiency of the technology. Although HASL had the highest BTU per hour rate of all the technologies, after normalizing the rate using the overall throughput (260,000 ssf), only the OSP (conveyorized and non-conveyorized), and the conveyorized HASL were more energy efficient than the HASL process. It also was found that for alternatives with both types of automation, the conveyorized version of the process is typically the more energy efficient (HASL and OSP), with the exception of the immersion tin process.

The rate of deposition of metal was calculated for each technology along with the total amount of metal consumed for 260,000 ssf of PWB produced. It was shown that the consumption of close to 300 pounds of lead (per 260,000 ssf) could be eliminated by replacing the baseline HASL process with an alternative technology (see Section 5.1, Resource Conservation). In cases where waste solder is not routinely recycled or reclaimed, the consumption of as much as 2,500 pounds of lead (per 260,000 ssf) could be eliminated by replacement of the HASL process. Although several of the alternative technologies rely on the use of small quantities of other metals (especially nickel, palladium, gold, silver, and tin) the OSP technology eliminates metal consumption entirely.

Social Benefits/Costs Assessment

The social benefits and costs of the surface finishing technologies were qualitatively assessed to compare the benefits and costs of switching from the baseline technology to an alternative, while considering both the private and external costs and benefits. Private costs typically include any direct costs incurred by the decision-maker and are generally reflected in the manufacturer's balance sheet. By contrast, external costs are not borne by the manufacturer, but by society. Therefore, the analysis considered both the impact of the alternative surface finishing processes on the manufacturer itself (private costs and benefits) and the impact the choice of an alternative had on external costs and benefits.

Table ES-9 presents an overview of potential private and external benefits and costs associated with the operation of the surface finishing line. Changes in the surface finishing technology employed could potentially result in a net benefit (a change in a beneficial direction) or cost (a change in a detrimental direction) in each of the categories listed below. The type of change and the magnitude will vary by facility.

Table ES-9. Overview of Potential Private and External Benefits or Costs

Evaluation Category	Private Benefit or Cost [a]	External Benefit or Cost [a]
Manufacturing costs	Capital costs, Materials (chemical) costs, Utility costs, Wastewater discharge costs, Production costs, and Maintenance costs.	NA
Occupational health/ Worker risk	Worker sick days, and Health insurance costs to the PWB manufacturer.	Medical costs to workers, and Pain and suffering associated with work-related illness.
Public health/ Population risk	Potential liability costs.	Medical costs, and Pain and suffering associated with illness.
Wastewater and Ecological risk	Treatment costs to meet wastewater permit requirements, Possible fines if permits are violated, and Increased liability costs.	Loss of ecosystem diversity; and Reduction in the recreational value of streams and rivers.
Energy use	Direct costs from the use of energy in the manufacturing process.	Increased air emissions, and Depletion of natural resources.
Water use	Direct costs from the use of water in the manufacturing process.	Water costs for the surrounding area, Costs paid to treatment facilities to clean the water, Changes to water quality available to society; and Reduced water supply.

[a] A benefit would be a change in a beneficial direction (e.g., *decreased* capitol costs), while a cost would be a detrimental change (e.g., *increased* worker sick days).

Each alternative presents a mixture of private and external benefits and costs. In terms of worker health risks, conveyorized processes have the greatest benefits for reduced worker inhalation exposure to bath chemicals; they are enclosed and vented to the atmosphere. However, dermal contact from bath maintenance activities can be of concern regardless of the equipment configuration for HASL and OSP processes, as well as non-conveyorized nickel/gold, nickel/palladium/gold, and immersion tin processes. Little or no improvement is seen in public health risks because results were below concern levels for all technologies. Differences in estimated wastewater contaminant levels and aquatic risk concerns suggest that alternatives to non-conveyorized HASL pose lower potential private and external costs (or higher benefits). Conveyorized processes consumed less water than that consumed by non-conveyorized processes, resulting in net private and external benefits. Only the OSP technology, along with the conveyorized HASL technology, are expected to reduce potential private and external costs of energy consumption, resulting in increased social benefits.

V. CONCLUSIONS

The CTSA evaluated the risk, competitiveness, and resource requirements of six technologies for performing the surface finishing function during PWB manufacturing. These technologies are HASL, nickel/gold, nickel/palladium/gold, OSP, immersion silver, and immersion tin.

The results of the CTSA analyses of the surface finishing technologies were mixed. Analyses of process costs, energy, and natural resource consumption each showed that some alternatives performed better than HASL, while others did not. An evaluation of potential occupational risks from both inhalation and dermal exposures indicated that several alternatives posed lower occupational risks than HASL, based on the number of chemicals with risk results above concern concentrations. Ecological risks posed by the alternatives were all lower than the HASL process, also based on the number of chemicals exceeding concern concentrations. None of the surface finishing technologies, including HASL, posed a risk to populations living nearby. Finally, alternatives to the traditional non-conveyorized HASL technology (the baseline process) were demonstrated to perform as well as HASL during performance testing; however, several of the alternatives improve upon the technical limitations of the HASL finish (e.g., wire-bondability, surface planarity).

Table ES-10 summarizes the CTSA analyses results for the surface finishing technologies, relative to the non-conveyorized HASL baseline. It is important to note that there are additional factors beyond those assessed in this CTSA that individual businesses may consider when choosing among alternatives. The actual decision of whether or not to implement an alternative is made outside of the CTSA process.

Table ES-10. Relative Benefits and Costs of Surface Finishing Alternatives Versus Baseline

Surface Finishing Technology	Production Costs ($/ssf)	Number of Chemicals of Concern				Water Consumption (gal/ssf)	Energy Consumption (Btu/ssf)
		Worker Health Risks [a,b,c]		Public Health Risks	High Aquatic Toxicity Concern [a]		
		Inhalation	Dermal	Inhalation			
HASL, Non-Conveyorized (BASELINE)	$0.36	1	2	0	4	1.24	218
HASL, Conveyorized	=	+	=	=	+	+	+
Nickel/Gold, Non-conveyorized	-	--	--	=	++	-	--
Nickel/Palladium/Gold, Non-Conveyorized	--	--	--	=	++	--	--
OSP, Non-conveyorized	++	=	-	=	++	+	+
OSP, Conveyorized	++	+	=	=	++	++	++
Immersion Silver, Conveyorized	+	+	+	=	++	++	-
Immersion Tin, Non-conveyorized	+	+	=	=	++	-	-
Immersion Tin, Conveyorized	+	+	+	=	++	+	--

[a] For technologies with more than one chemical supplier (e.g., nickel/gold, OSP, immersion tin) all chemicals may not be present in any one product line.
[b] For the most exposed individual (e.g., a surface finishing line operator).
[c] Because the risk characterization did not estimate the number of incidences of adverse health outcomes, the amount of reduced risk benefit cannot be quantified. The comparison shown in this table is based on the number of chemicals of concern for the baseline.

Key:

=	Neutral, less than 10% increase or decrease from baseline.
-	10 to 100 percent worse.
--	100 percent worse.
+	Some benefit, 10 to 50 percent decrease from baseline.
++	Greater benefit, +50 percent or greater decrease from baseline.

To assist PWB manufacturers who are considering the implementation of an alternative surface finish, the DfE PWB Project has prepared an implementation guide that describes lessons learned by other PWB manufacturers who have begun using an alternative surface finishing process.[4] In addition, the University of Tennessee Department of Industrial Engineering can provide technical support to facilities that would like to use the cost model developed for the CTSA to estimate their own manufacturing costs should they switch to a surface finishing alternative.

[4] *Implementing Cleaner Printed Wiring Board Technologies: Surface Finishes* (EPA 744-R-00-002, March 2000). This and other DfE PWB Project documents can be obtained by contacting EPA's Pollution Prevention Information Clearinghouse at (202) 260-1023 or from www.epa.gov/dfe/pwb.

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